LARP

High Luminosity LHC

QXF Conductor and Cable

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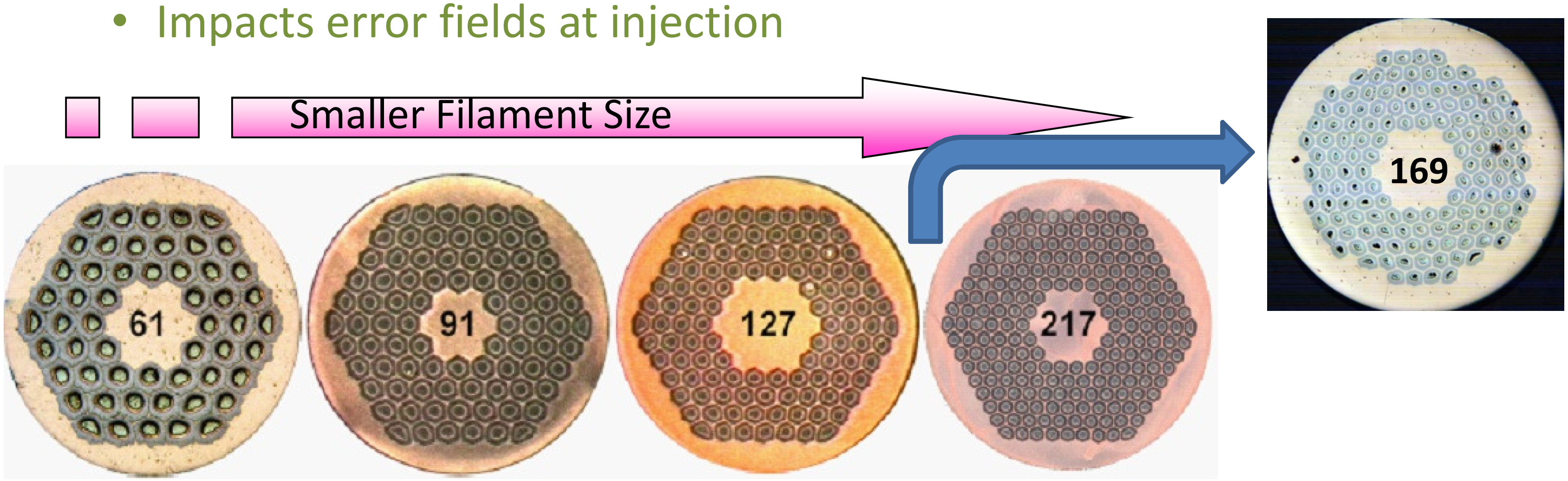
Feb-17-2014

Outline

1. Introduction
2. QXF Magnet Strand
3. Strand Procurement Plan
4. QXF Cable
5. Cable Insulation
6. Summary

Introduction

- The long 90 mm quad-magnet LQS01 used 0.7 mm RRP® 54/61 Ta-Ternary strand from Oxford Superconducting Technology
- Subsequent LQ and HQ magnets used 108/127 strands
  - Smaller sub-elements minimizes flux jumps and improves stability.
  - Leads to smaller Filament Magnetization
    - Impacts error fields at injection



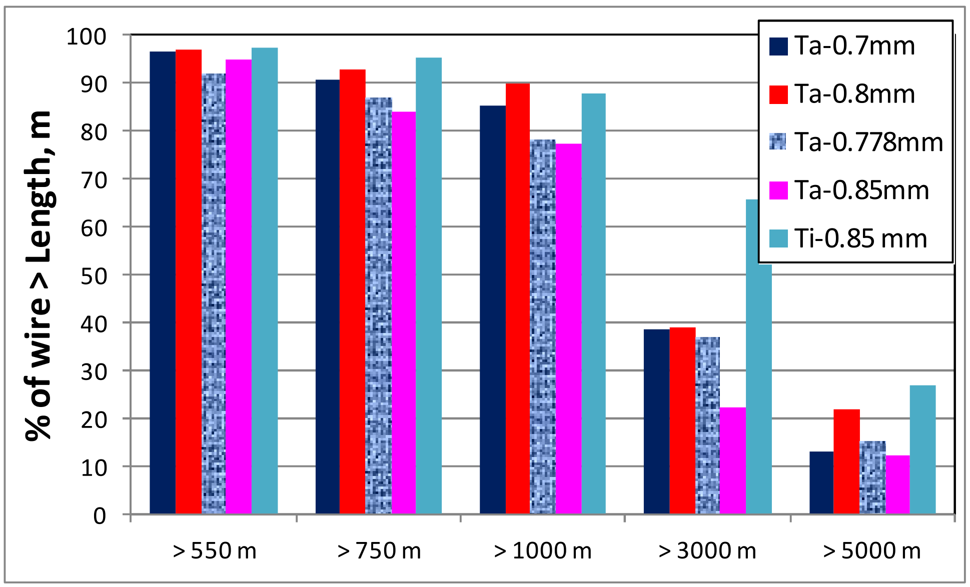
RRP® 108/127

- 108/127, 0.7 mm first delivery of 90 kg in Feb-2008 under CDP contract
  - Used in TQS03 – a very successful 90 mm magnet
- 2009-2012 substantial wire produced at 0.7 mm for LQ and 0.8 (0.778 mm) for the 120 mm quad, HQ
  - Ta-Ternary : $(Nb – 7.5\ wt.\%\ Ta)_3Sn$
  - 1300 Kg produced for LARP
    - Successful LQ03 and HQ02 magnets

- 108/127 Ti-Ternary : CDP development 2009
  - Uses Nb and Nb-Ti rods (provides Ti source) in sub-element
  - *Exhibits higher strain tolerance than Ta-Ternary*
- 2012-2013 : 410 Kg of Ti-Ternary wire manufactured
    - Good piece length at 0.85 mm diameter

OST production of 108/127 for LARP

Km	Kg	Type/Dia	% of wire > Length, m					# Billets	Billet Yield, Kg
			> 550 m	> 750 m	> 1000 m	> 3000 m	> 5000 m		
78	264	Ta-0.7mm	96.7	90.8	85.3	38.7	13.1	9	31
62	260	Ta-0.8mm	97.1	92.8	89.8	39.0	21.8	9	29
136	570	Ta-0.778mm	92.0	86.9	78.3	37.1	15.1	21	27
41	206	Ta-0.85mm	95.0	83.9	77.5	22.4	12.3	8	26
83	410	Ti-0.85 mm	97.6	95.2	87.9	65.6	26.9	12	34

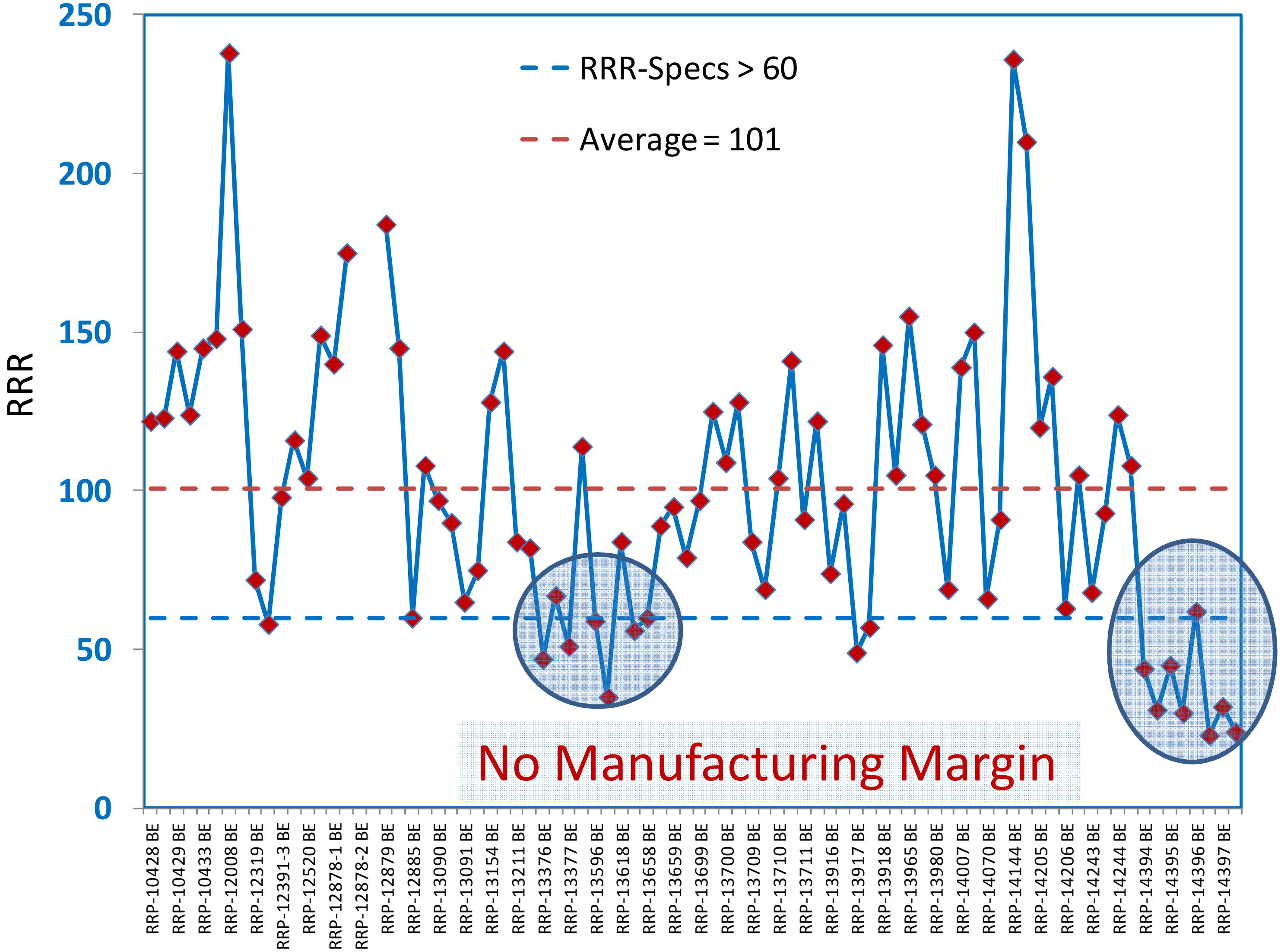


Ti-Ternary piece-length better than Ta-Ternary

Performance Highlights of Ta-108/127

- OST qualified wires using the following HT schedule
  - 210°C/48h + 400°C/48h + 665°C/50h
- Overall, a very large fraction of the billets surpassed the J_c (non-Cu critical current density) minimum of 2650 A/mm^2 at 12 T, 4.2 K.
- However, there was little manufacturing margin in meeting the RRR (Residual Resistance Ratio of copper stabilizer) minimum of 60.
  - To meet the specs. the HT temperature had to be lowered to 650 °C/48h or lower. J_c is lower at the lower temperatures.
- For the LQ coils (0.7 mm) the reaction temperature was further reduced to 640 °C/48h so that the RRR of extracted strands was > 60, and for HQ (0.778 mm), 650 °C/48h was used to maintain a RRR > 100.

OST data 0.8/0.778 mm 108/127



Optimizing Sn-content for RRR control

MT-23

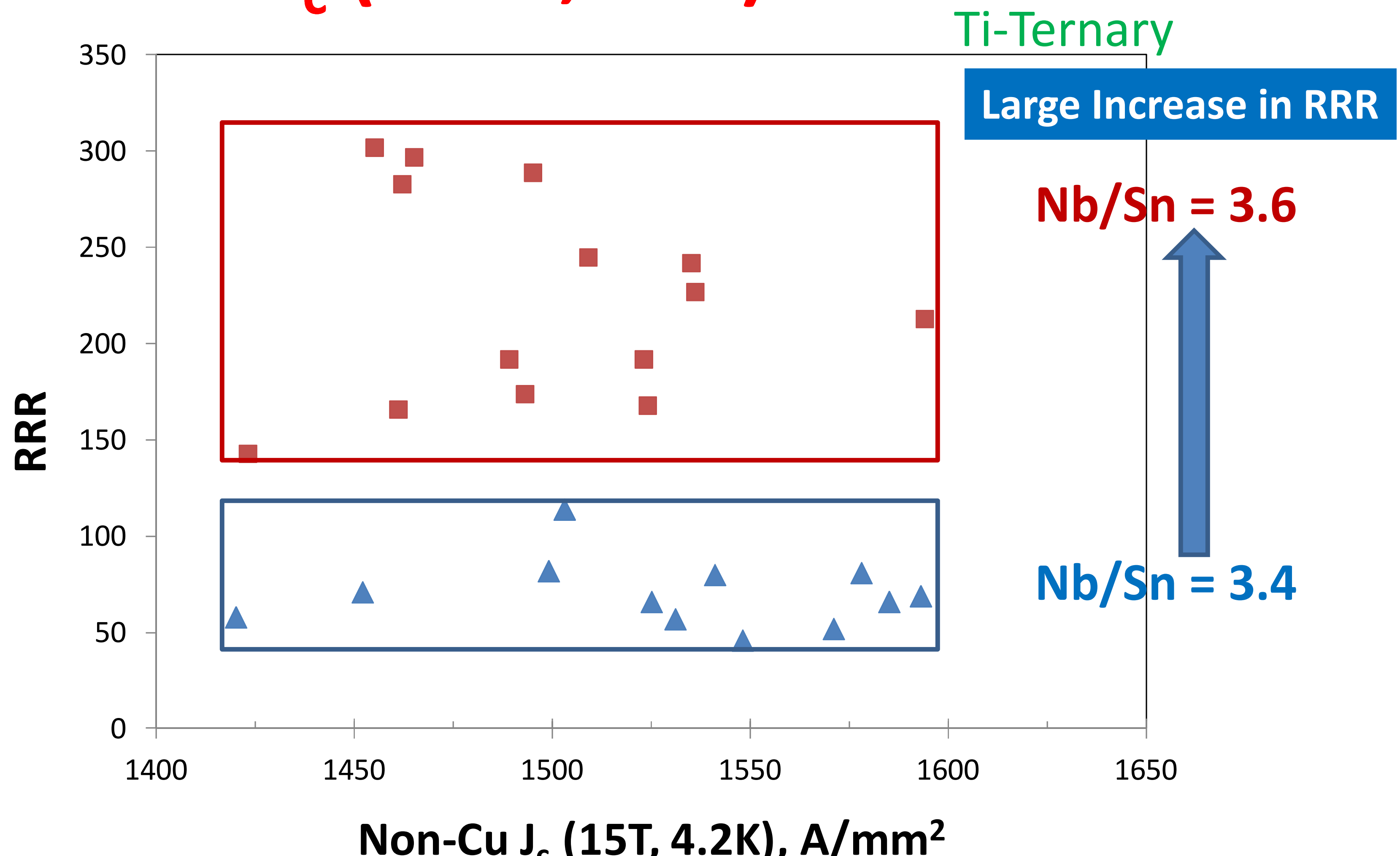
Optimizing Nb_3Sn Conductors for High Field Applications

Michael B. Field, Youzhu Zhang, Hanping Miao, Michael Gerace and Jeffery A. Parrell

"As an example of what is possible to achieve through fine control of the Nb:Sn ratio, we produced several hundred kilograms of Ti doped 0.778 mm diameter (*D_s = 50 μm)* strand, with half of the billets receiving a Nb:Sn atomic ratio of 3.4:1, and half the billets with reduced tin so as to raise the Nb:Sn ratio to 3.6:1. As demonstrated in Fig. 3, the effect was substantial on the samples given a 650 °C/50 hr peak heat treatment, with a nearly three-fold increase in average RRR and little corresponding sacrifice in J_c at 12 T."

LARP 400 kg lot order

OST Data for 0. 778 mm wire J_c (4.2 K, 15T) vs. RRR



2 year development cycle

Outline

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Strand Functional Specification for the HiLumi Project

- In late Oct'2013 we had an internal LARP-CERN review of the strand and cable for the MQXF magnets.
- Subsequently within a Conductor Working Group with members from CERN and LARP we agreed on a set of functional requirements for the strand and cable
- In the vey near future these requirements will be codified in a Conceptual Specification document that will be in the CERN EDMS system for the HiLumi-LHC Project.

Functional Specification for QXF Strand

Process	Ti-Ternary RRP® Nb3Sn
Strand Diameter, mm	0.85 ± .003
Ic(15 T) at 4.2 K, A	> 361
n-value	> 30
Ds, µm (sub-element diameter)	< 50
Cu : Non-Cu volume Ratio	1.2 ± 0.1
RRR (after full reaction)	≥ 150
Twist Pitch, mm	19 ± 2
Twist Direction	Right-hand screw
Strand Spring Back, deg.	< 720
Magnetization Width at 3 T, 4.2 K, mT	< 300
Minimum Piece length, m	TBD
High temperature HT duration, h	≥ 48

Reduced-Sn content to obtain high RRR

J_c(15 T) > 1400 A/mm^2

132/169

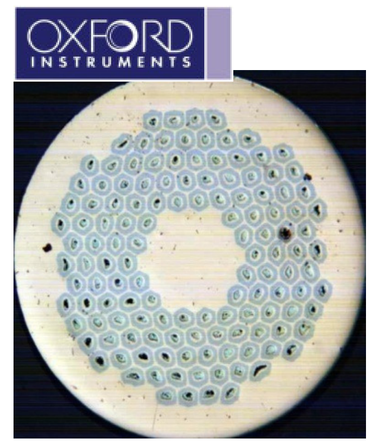
Residual Resistivity Ratio

132/169 design wire

- Motivation for adopting 132/169 design wire
  - OST has accumulated considerable manufacturing experience making strand for FNAL and CERN

Table of Sub-element diameter in μm

Strand Design	54/61	84/91	108/127	132/169	192/217
		Cu/Non-Cu= 1.2			
			# of Sub-elements		
D_w, mm	**54**	**84**	**108**	**132**	**192**
0.9	83	66	58	53	44
0.85	78	63	55	50	41
0.778	71	57	50	46	38
0.7	64	52	45	41	34



- 0.85 mm strand with132 filaments *has the same sub-element size* as 0.778 mm with 108 filaments used in HQ

RRP 132/169 production for CERN

Slide from Amalia Ballarino/CERN

		Quantity Procured (km)		
	Wire Φ (mm)	**RRP® 132/169**	**PIT 114**	**PIT 192**
FRESCA 2	**1**	10+15+18+45	-	1+9+15+15+45
Hi-Lumi Quad	**0.85**	5 + 35	-	5 + 35
11 T	**0.7**	30 + 150	3 + 22.4*+ 50	-
Total length		**308**	**75.4**	**125**

1.29 tons RRP® 132/169

Hi-Lumi quadrupole RRP® strand (Φ=0.85 mm)

RRP 132/169

Slide from Amalia Ballarino/CERN

Billet ID 0.85 mm 132/169	Jc (4.2 K,15T) A/mm² OST	Jc (4.2 K,12T) A/mm² OST	Jc (4.2 K,12T) A/mm² CERN	RRR CERN
14842	1512/1498	2888/2900	2830/2752	160/212
14393	1440/1451	2881/2877	2808/2744 2776/2666	232/186 201/196
14310	1510/1598	2966/3023	2757/2820	210/215
14839	1463/1425	2842/2835	2800	189
Average value	**1490 A/mm²**	**2900 A/mm²**	**2770 A/mm²**	**180**

Cu/non Cu ratio: 1.21 -1.35

50 hours at 640 °C

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Implementing 132/169 in LARP

- For LARP QXF magnet
  - SQXF1 Magnet will use 108/127 strand
  - Presenting a plan to use 169-strand in SQXF3 and in LQXF magnets
- With CDP funds, contracts at OST:
  - FY-13 190 kg of 132 filament strand with "Reduced-Sn" (in-manufacture)
  - FY'14 350 kg of 132 filament strand with "Reduced-Sn"(PO pending)
  - FY'15 250 kg of 132 filament strand with "Reduced-Sn" (planned)
  - FY'16 250 kg of 132 filament strand with "Reduced-Sn" (under discussion with CDP?)
- LARP has an existing PO of 255 Kg for 108/127 meeting the specification shown previously
  - Converted to 169- strand with "reduced-Sn". 10% increase in cost
- Additional orders to be placed in FY15 and FY16:
  - 1300 Kg, in two lots of 550 Kg (or 300 ?) and 650 Kg

Procurement Plan for QXF magnets

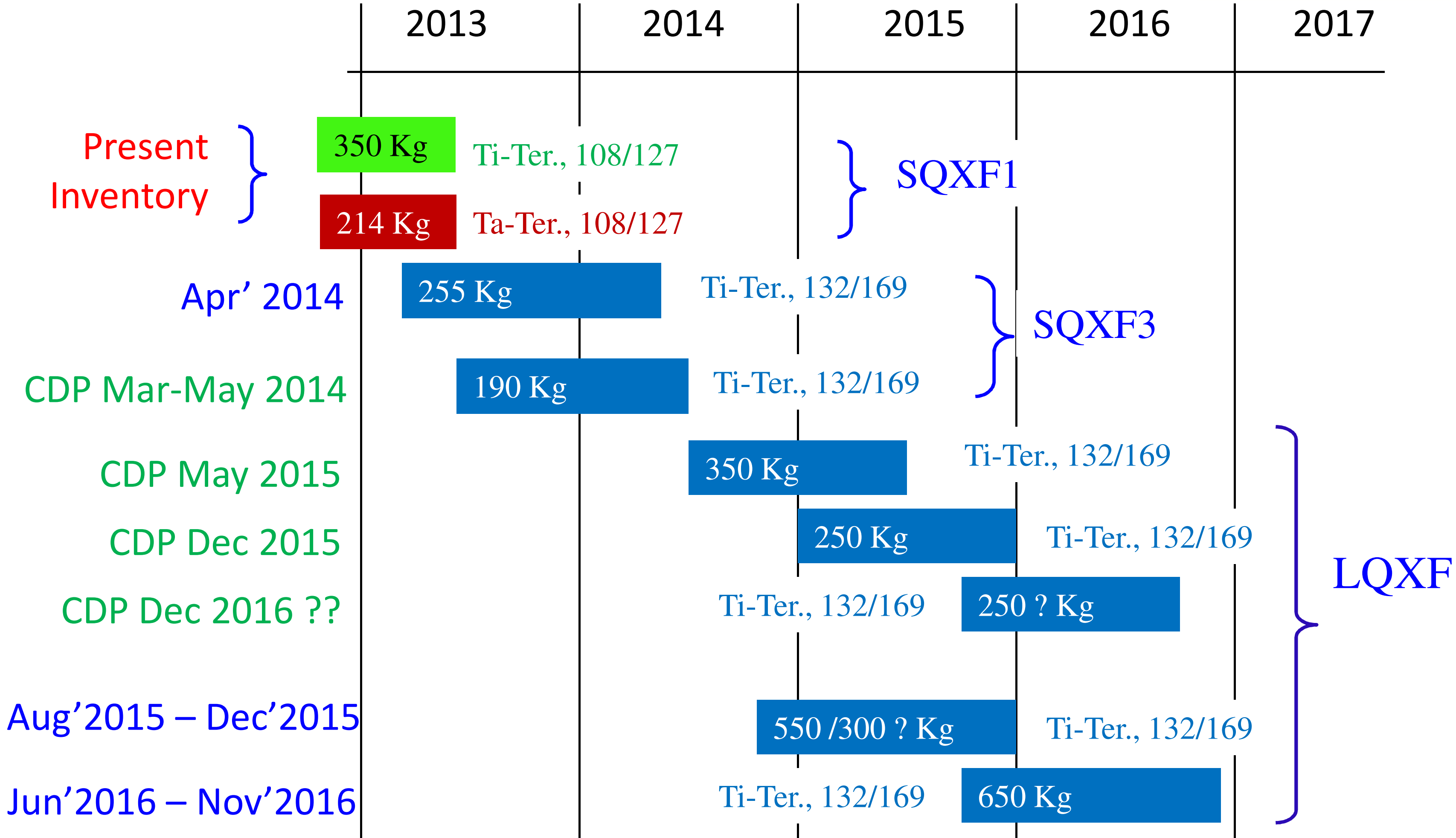
SQXF

- Require 11 + 2 PC coils for SQXF; unit length (UL) 170 m
  - Assuming 10% loss in strand from cable mapping
  - Total length of strand for SQXF: ~ 94 km (470 Kg)
- PC coils use 108/127 Ta-Ternary (in inventory)
- SQXF1: 6 coils, 108/127 Ti-Ternary (in inventory)
- SQXF3: 5 coils, 132/169 (strand in process)

LQXF

- Require 16 + 2 PC coils for LQXF; unit length (UL) 450 m
  - Total length required for LQXF: ~ 353 km (1760 Kg)
- PC: 1 UL , 108/127 (in inventory), 1 UL, 132/169 (strand in process)
- C03: mirror test (strand in process)
- C04-C18 (to be ordered within LARP and CDP)

Procurement plan 0.85 mm strand



5 Kg is equivalent to 1 km of wire

Typical present RRP billet yield is ~ 35 Kg / 7Km

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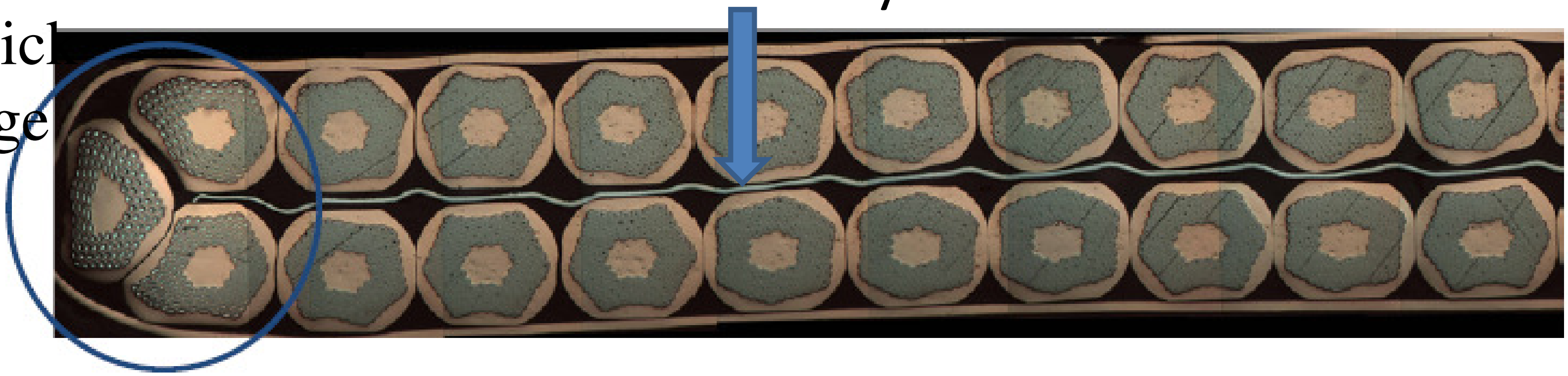
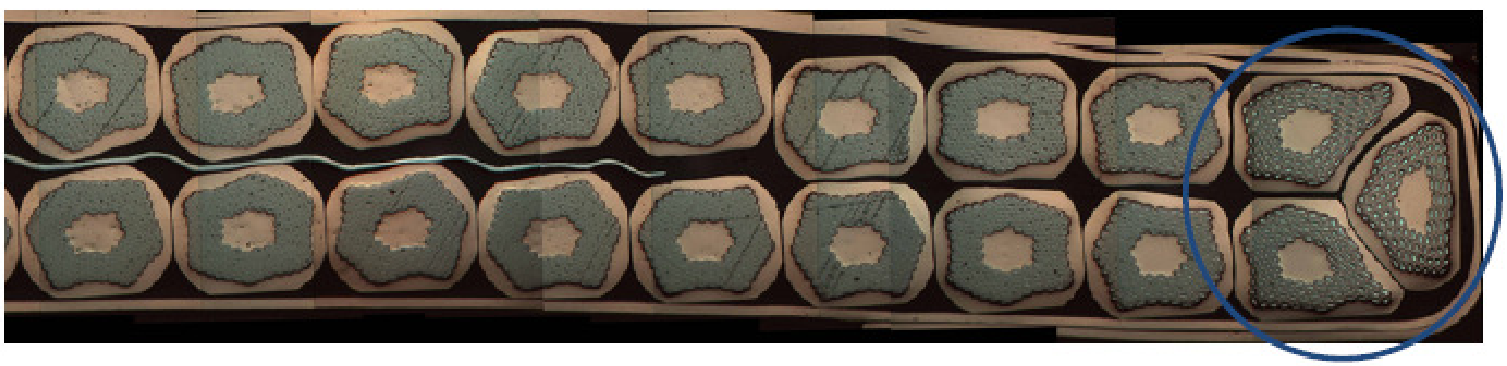
18 mm wide 40 strand QXF cable Development at LBNL and CERN

SS Core to reduce Eddy Current losses

Thick edge





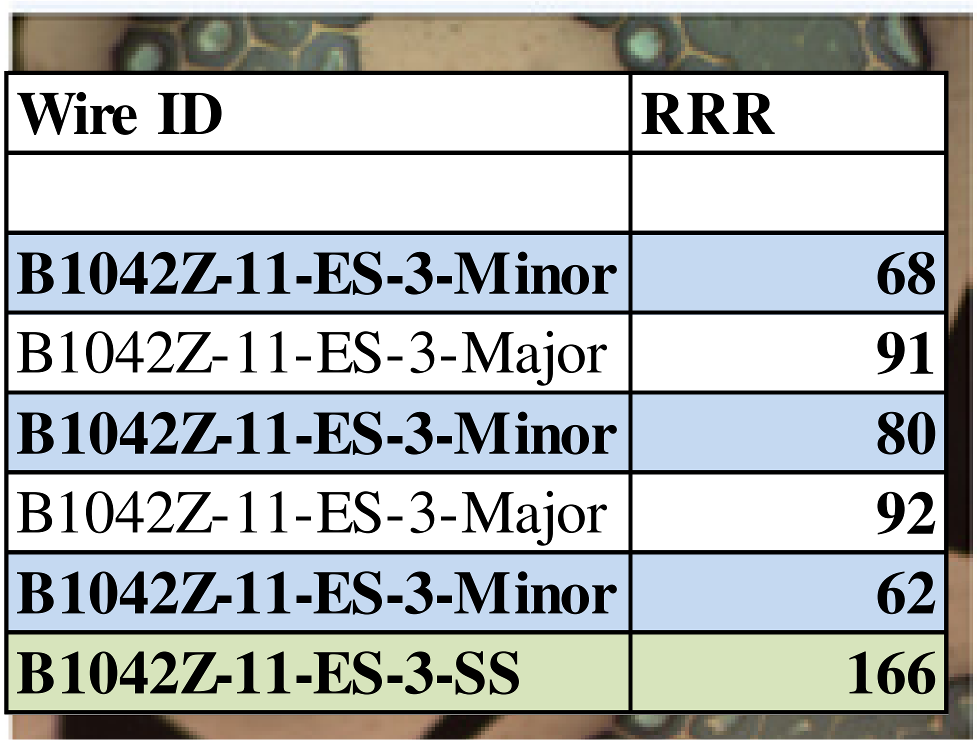
Width =	17.95 mm
Thickness =	1.50 mm
PL =	95.5 mm

Cable 1042Z-12

Thin Edge

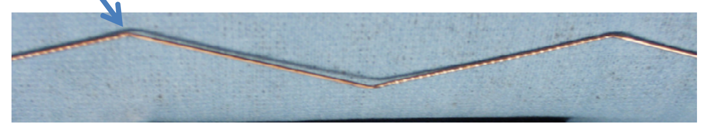
Cabling Trade-offs

- Minimize the amount of strand damage
  - Less compaction
  - Can lead to mechanically unstable cable for coil winding
- Increase mechanical stability of cable
  - More compaction and deformation of strands
  - More strand damage - Reduced critical current and RRR (Sub-element shear leading to barrier thinning and barrier breakage causing Sn leak into copper and reducing RRR)
  - LBNL is using a Strand Damage Score to evaluate damage to sub-elements using microscopy of cable x-sections



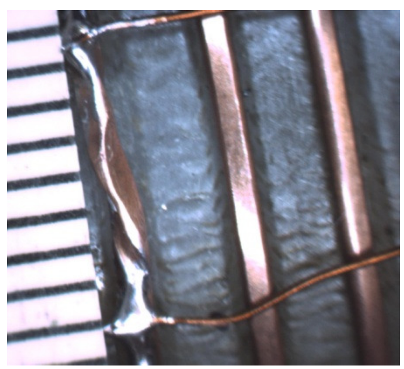
Wire ID	RRR
B1042Z-11-ES-3-Minor	**68**
B1042Z-11-ES-3-Major	**91**
B1042Z-11-ES-3-Minor	**80**
B1042Z-11-ES-3-Major	**92**
B1042Z-11-ES-3-Minor	**62**
B1042Z-11-ES-3-SS	**166**

These damage lead to mostly RRR degradation of the copper stabilizer at the edges of the cable. Low RRR can lead to conductor instability due to "magnetization" and "self-field" effects. Target is to maintain RRR > 100 at the "kinks"



Example of sub-element shearing and barrier rupture

V-tap configuration to measure RRR at edges



Draft Specification for LARP/CERN QXF Cable

• Number of strands	40
• Mid-thickness	1.525 mm +/- 0.010 mm
• Width	18.15 mm +/- 0.050 mm
• K.S. angle	0.55 deg. +/- 0.10 deg.
• Pitch Length	109 mm +/- 3 mm
• Core Material	Annealed 316L SS
• Core Width	12.5 -14.7 mm (TBD)
• Core thickness	0.025 mm

- Cables, made with RRP strands, using these parameters are not fully mechanically stable during coil winding
  - Occasional "popped strands"
- At this time cables are being managed during coil winding by using a winding block and ceramic binder on the fiberglass insulation (see Presentation by Miao Yu)

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Cable Insulation

- Insulation is braided directly on cable
  - New England Wire Technology (NEWT)
- Using S-2® glass (from AGY) with 933 Silane sizing
  - Product literature: 933 sizing is stable at processing of temperature of 670°F and above
  - Trials at LBNL show that 2% by weight is lost by heat treating at 665C
  - CERN is also braiding with the same yarn.
  - Tests at CERN to 650°C show no decomposition of the sizing.
  - Compatible with CTD-101K Epoxy

"Improved S-2 Glass Fabric Insulation for Nb_3Sn Rutherford Cable"
Raymond Blackburn, David Fecko, Andrew Jaisle, Al McInturff, Peter McIntyre, and Tom Story
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 2, JUNE 2008, p 1391

Braided Insulation

- HQ03 used cable with braided insulation, 0.100 ± 0.005 mm thick. Braided insulation replaced pre -fabricated sleeve used in LARP magnets
- Several lengths of QXF cable has been insulated
  - Using braiding parameters to yield target specification of 0.145 ± 0.005 mm thickness (CERN driven requirement for electrical insulation)
  - 10-stack measurements at 5 MPa are used to determine insulation thickness
  - Thickness can be readily adjusted to meet any change to present specification.

Strand Procurement and Cabling Schedule

- For LARP QXF magnet
  - Procurement and Cabling schedule set by the demands of coil fabrication
- Cabling start is set 4 months before start of coil winding
  - Typical time for cabling at LBNL is 2 weeks
  - Braided Insulation at New England Wire
    - 2- 4 weeks
- Strand procurement time is presently at 13 months
  - Partial delivery starts as early as 9 months for large orders

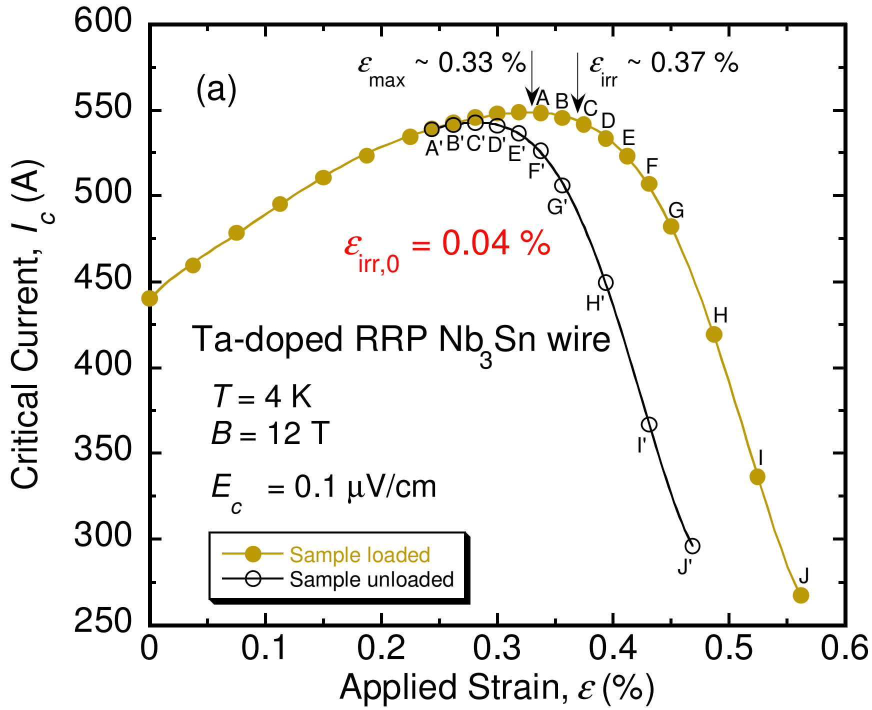
Summary

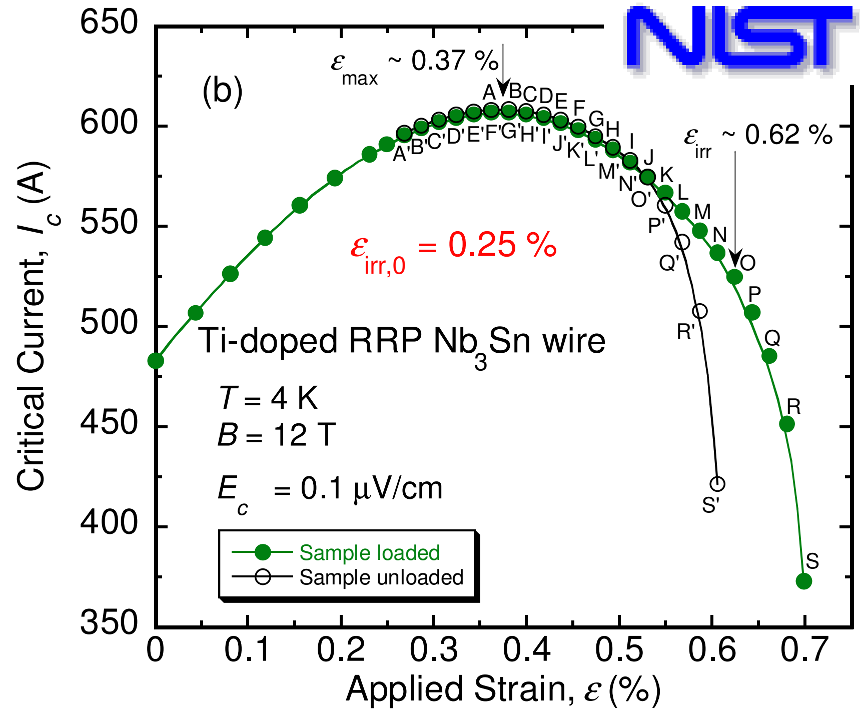
- RRP® wire can meet I_c spec with adequate margin
- The "reduced-Sn" design change increases RRR control with minimal loss of J_c.
  - Implemented for all billets in process and future procurements.
- Strand Specification for MQXF wire will soon be formalized in the CERN EDMS system for the HiLumi Project
- LARP plan implements 132/169-strand in SQXF3 magnet and all LQXF prototypes.
- Strand procurement has been planned to meet cable manufacture and coil winding schedule.
- We have a 1st iteration of the cable parameters. Final parameters will be set after sufficient cabling experience – June'14
- Specification and Production QA plan to be finalized this fiscal year for strand, cable and insulation

End of Presentation

Extra Slides

Ta-Ternary vs. Ti-Ternary 0.7 mm strand from CDP





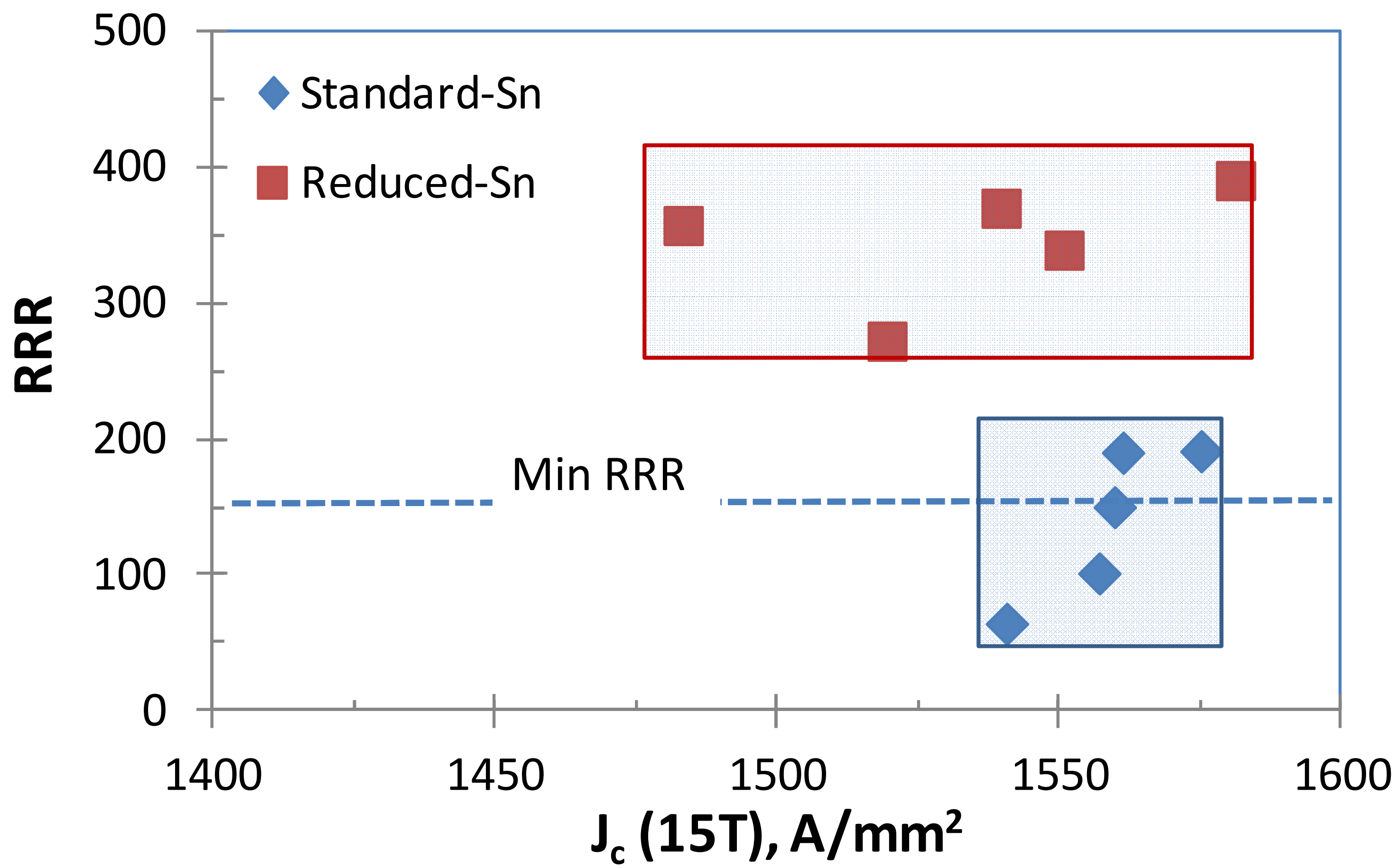
Ti-doped Nb_3Sn wire more strain tolerant than Ta-doped

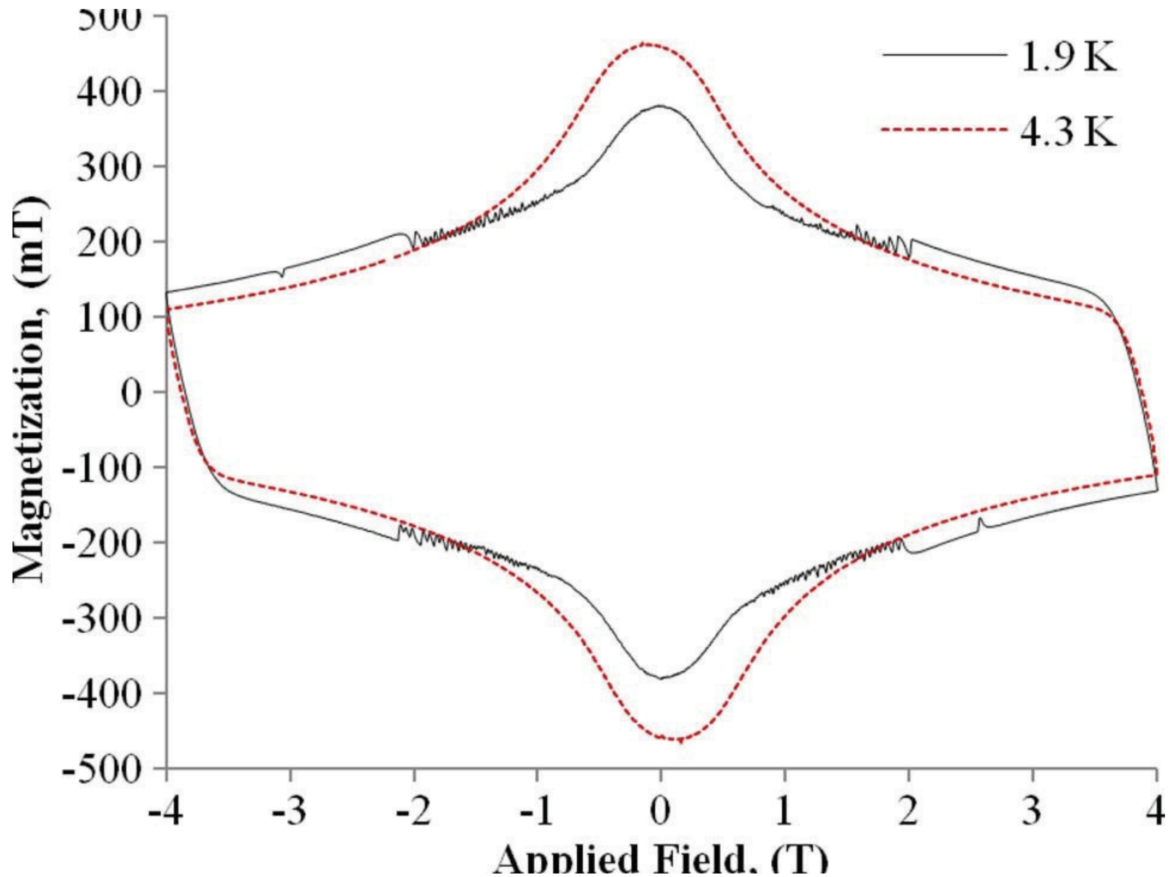
This has been confirmed for 0.8 mm $(Nb\text{-}1.5\ at\%\ Ti)_3\text{-}Sn$ strand ε_{irr} = 0.32-0.35 % as well as strands with 108 and192 filaments. Expect 169 design to be similar.

Inf
pr
N. Cheggour, L. F. Goodrich, T. C. Stauffer, J. D. Splett, and X.F. Lu, A. K. Ghosh, G. Ambrosio
Supercond. Sci. and Tech., 20, (2010)

J_c (4.2 K, 15T) and RRR for 0. 85 mm Ti-Ternary wire (LARP Data)

210C/48h + 400C/48h + 640C/72h





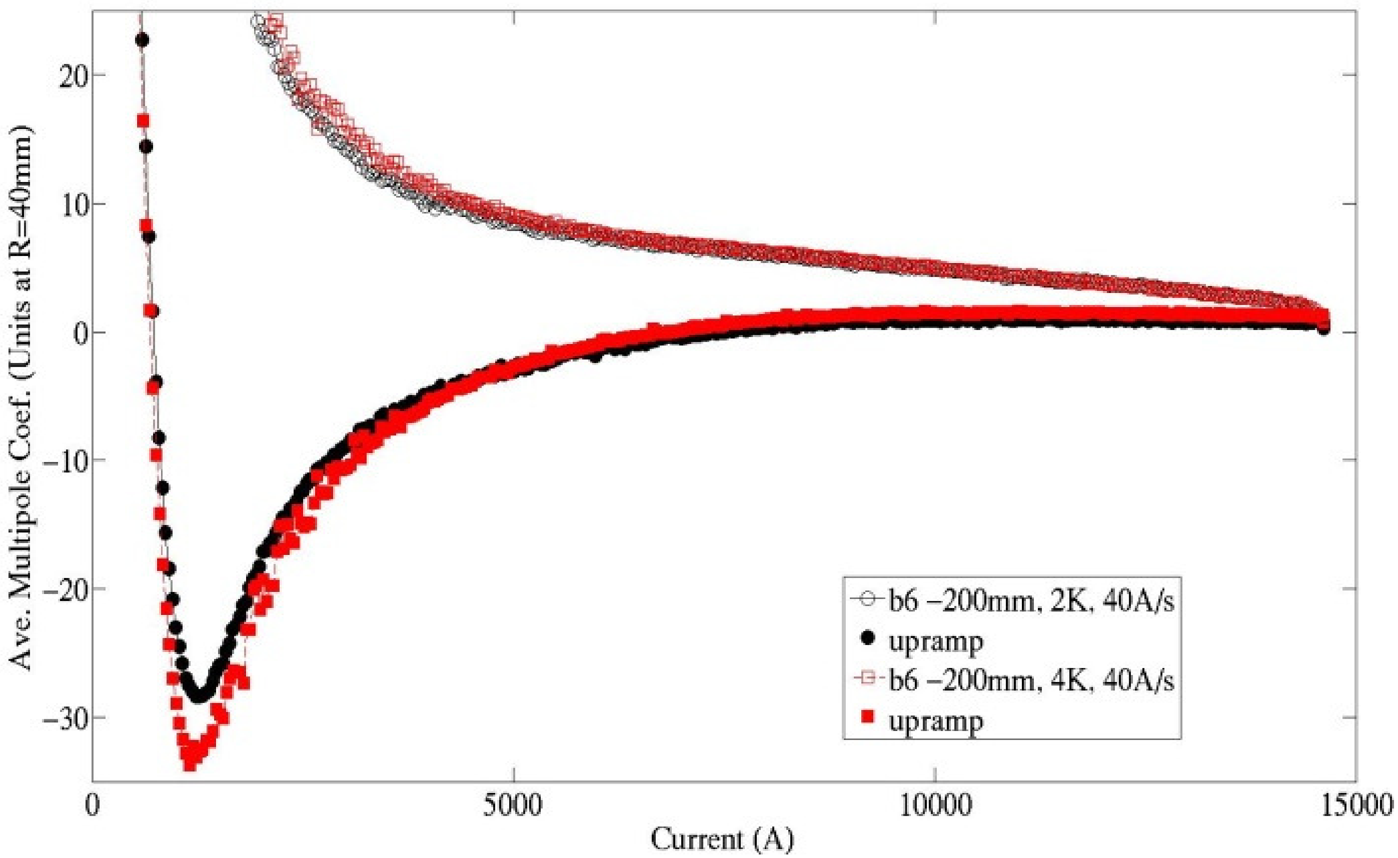
Magnetization as a function of applied field for 108/127 Ti-doped sample

Magnetization Measurements of High-J_c Nb_3Sn Strands
B. Bordini et al., *IEEE Trans. Appl. Supercond.*, vol. 23, pp. 7100806, 2013

Harmonic Field b6 in HQ02 4 K and 2 K

Strand is 0.778 mm, 108/127

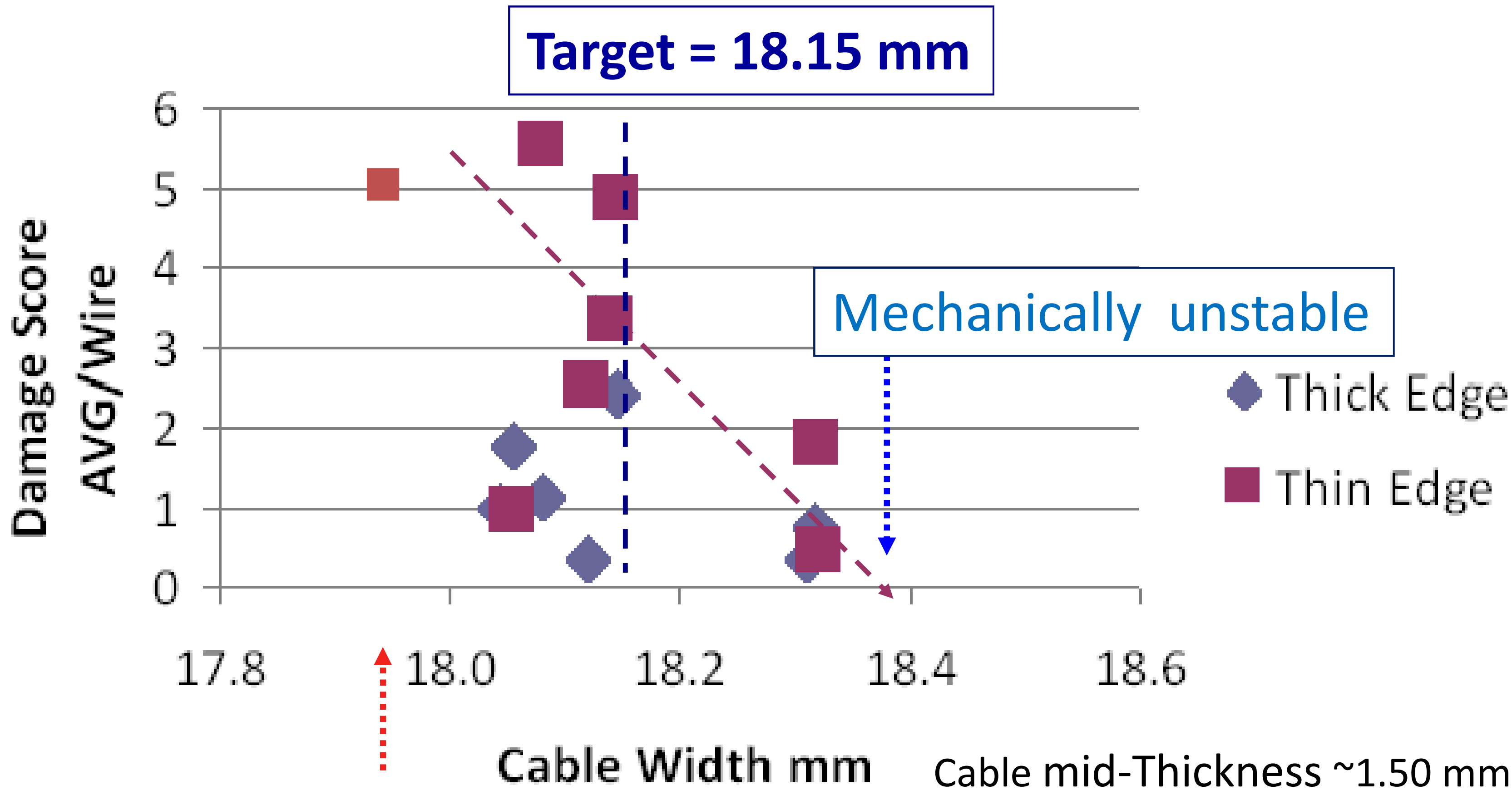
Flux-jump effect decreases from 4.2 to 2 K



Taken from Project Schedule

Task Name	Duration	Start	Finish
CDP Procurement 1, 180 kg	262 days	Thu 5/23/13	Fri 5/30/14
LARP Procurement 1, 275 kg	288 days	Mon 3/25/13	Tue 5/6/14
CDP Procurement 2, 350 kg	286 days	Fri 4/11/14	Fri 5/29/15
CDP Procurement 3, 250 kg	300 days	Mon 10/13/14	Mon 12/21/15
LARP Procurement 2, 550 kg	300 days	Mon 10/13/14	Mon 12/21/15
LARP Procurement 3, 650 Kg	250 days	Thu 10/15/15	Tue 10/11/16

Damage Score vs. QXF Cable Width
Pitch Length of 109 mm

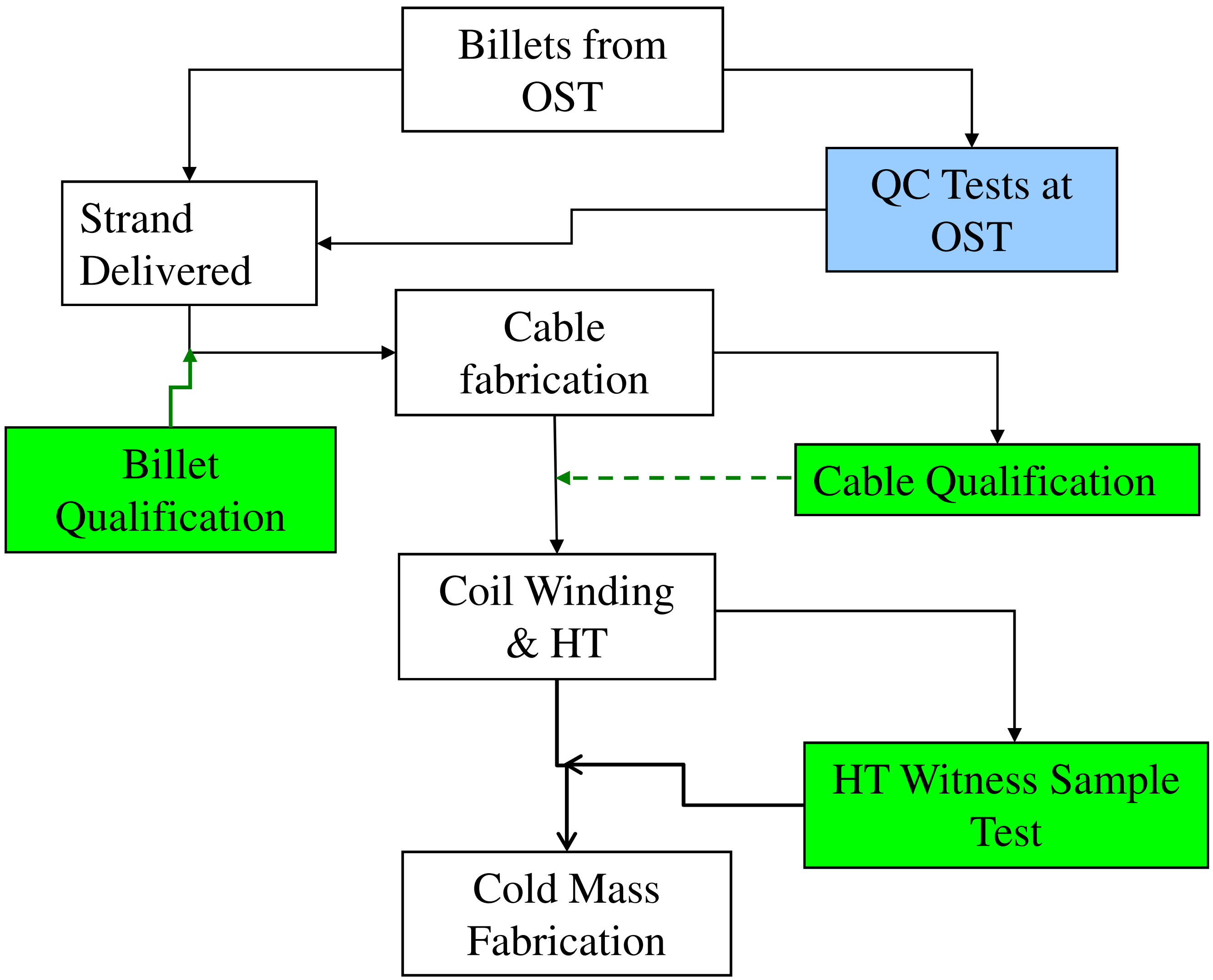


Need 17.95 mm width for Mechanical stability

Cable Risk and Impact on Magnets

1. Strand stability (High risk)
   - Want high stability current
   - **Require minimum RRR > 100 at kinks of extracted strands**
   - RRR > 150 in strand to assist in getting RRR > 100 at kinks
2. Cable winding stability (Medium risk)
   - Assume cable can be managed cable during coil winding
3. Strand I_c loss due to cabling, < 5 % (Low risk)
   - I_c of extracted strands at 12 T, 4.2 K ~730 A
   - I_c at 140 T/m operation at 12 T, 1.9 K ~440A
4. Stress sensitivity of cable with damaged strands (Unknown Risk)

QC-Plan


Billets from OST
QC Tests at OST
Strand Delivered
Cable fabrication
Billet Qualification
Cable Qualification
Coil Winding & HT
HT Witness Sample Test
Cold Mass Fabrication